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Seismic Exploration

The present invention relates to seismic exploration techniques and the seismic imaging of subsurface layers. It is particularly but not exclusively concerned

5   with submarine seismic exploration and with producing seismic survey reports of subsea geological structures.

Conventional seismic methods for exploring subterranean strata beneath the seabed involve generating a seismic wave and measuring the response. The

10   seismic wave may be simple or complex and may be generated at sea level, beneath the surface of the water or at the seabed. The response is detected by a series of spaced receivers which are commonly positioned on cables towed behind an exploration vessel. Generally, the receivers are held stationary for the detection step and are then moved to a different location and the process is

15   repeated.

The response to a seismic event in the solid rock at the sea floor includes a compression wave (P-wave) and a shear wave (S-wave). P-waves are considered well suited to imaging structures while the combination of S-waves

20   is well suited to determining rock and fluid characteristics. P-waves travel through rock and sea water while S-waves travel through rock only. Thus, if the receivers are hydrophones floating at or beneath the surface, they will detect only the P-waves. In order to detect the S-waves, it is necessary to use geophones located at the seabed.

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It has also been recognised that better seismic imaging can be achieved by making use of both P- and S-waves. However, the costs involved in positioning and re-positioning geophones on the sea bed in addition to the use of hydrophones has been found to be prohibitively costly. This is particularly

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so since in order to detect S-waves effectively, three independent orthogonal geophones are required at each recording location.

Specifically, it has been known for more than 10 years that 4C seismic imaging

5   of the subsurface may add more and better information to exploration due to high quality recording of shear waves (S-waves) at the water bottom. Unfortunately, 4C-imaging did not become the success that was expected, primarily due to the combination of extreme high acquisition cost and uncertainties in the prediction of payback. The cost factor is related to capacity

10   problems in available acquisition techniques.

4C recording is normally carried out by a hydrophone and three independent orthogonal geophones. The geophones are coupled to the sea bottom and they are therefore sensitive to the particle velocities generated by both the seismic p-

15   waves and the s-waves. These techniques use either sensor cables at the sea bottom or geophone nodes resting on or planted in the sea bottom. 4C seismic acquisition consists of a sequence of moving source and moving receiver operations. After an independent source vessel has carried out a series of shooting profiles, the bottom equipment has to be moved into the next position.

20   Both due to this static recording component in the acquisition and due to a limited number of available receivers, these 4C acquisition systems become ineffective. Due to physical problems both related to moving the heavy equipment along the water bottom and geophone coupling, the reliability is adversely affected.

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Finally, it is also recognised that the cost effectiveness of carrying out such seismic imaging, and in particular S-wave measurements, could be greatly reduced by avoiding the need to locate detection apparatus at the seabed, that is to measure an S-wave from a position spaced from the seabed and so allow

effective re-positioning of the detection apparatus with respect to the seabed. However, as mentioned, S-waves do not travel through sea water, making direct sensing remote from the seabed impossible. Remote sensing has further inherent problems in that the detection apparatus is subjected to ocean currents

5   which can inhibit effective positioning of the detection apparatus, and introduce noise into measurements, making correlation of the results very difficult.

It is therefore an object of the invention to provide a method of seismic
10   exploration in which both P-waves and S-waves are detected but which is simpler and less costly than known techniques.

According to one aspect of the invention, there is provided a method of seismic exploration which comprises: generating a seismic event; applying the seismic
15   event to the earth's surface; detecting a response to the event, the detected response including P-waves and S-waves in the earth's surface; and analysing the detected response; and in which: the detecting step comprises monitoring and recording the response to the seismic event in the form of movements of particles at the earth's surface, from a position spaced from the earth's surface,
20   the detecting step being carried out over a response period, the response period being a predetermined period of time after the seismic event; and the analysing step comprises analysing the movements of particles at the earth's surface in the recorded response to the seismic event during the response period.

25   According to another aspect of the invention, there is provided apparatus for carrying out seismic exploration which comprises: means for generating a seismic event; means for applying the seismic event to the earth's surface; detecting apparatus for detecting a response to the event including P-waves and S-waves in the earth's surface; and means for analysing the detected response;

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and in which: the detecting apparatus comprises monitoring apparatus and recording apparatus arranged to monitor and record the response to the seismic event in the form of movements of particles at the earth's surface, from a position spaced from the earth's surface, over a predetermined response period

5   after the seismic event. The invention also extends to a method for the production of a seismic survey report, using the method and/or apparatus set out above, and also to a report produced in this way.

The particles at the surface will respond both to P-wave and S-wave

10   stimulation and so their movements will be representative of the two waves. Since these movements are detected from a distance, the disadvantages of the prior art are avoided with there being no need to make contact with the surface and therefore no need to disengage before repositioning the detecting apparatus.

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Preferably, the movements of the particles are monitored using light, in the form of visible light, x-rays, UV light or IR light, or using another form of radiation including radio waves, radar, sonar or using acoustic waves, in positioning principles from photogrammetry including interference

20   measurements and acoustic positioning. The monitoring apparatus may be kept stationary during the response period and is then moved to a different position after the response period, and the method is then repeated. Alternatively, it may be moved relative to the earth's surface during the response period; the analysing step then preferably includes the elimination from the detected

25   response of noise caused by the relative movement of the monitoring apparatus.

The monitoring apparatus preferably comprises several monitoring devices which are used simultaneously at different locations. Preferably, the response is transformed to and recorded in digital form. Preferably, the analysing step

comprises analysing surface particle displacements and/or velocities and/or accelerations by measurements of changes in the distance (velocity) between a monitoring device such as a camera and the surface and the camera velocity. The camera velocity can be measured separately by three camera mounted

5   accelerometers.

The z-component of the surface particle velocity is similar to the pressure component which will be measured with a mounted hydrophone on the monitoring device. This redundant measurement can be used to calibrate the

10   system and make it more robust against ambient noise and system noise.

In a preferred embodiment, the monitoring apparatus comprises three sources of coherent mono frequency light directed at the surface area being monitored, and a receiver for the reflected coherent light beam. Preferably, the coherent

15   light and a reference light beam are used to make speckle patterns by means of interferometry, and by monitoring the time variation in light intensity within a subset of speckles, the 3D-particle velocity in the surface can be calculated using interferometry principles.

20   With such measurements, the spatially and temporally coherent reference beam is scattered from the seabed and the seabed being a diffuse surface, produces a specular reflection. This specular reflection scattered from the seabed is the contribution of many scattered wavelets which have a constant relative phase determined by the optical path-length from each point on the seabed.

25   Combining the reflected light with the coherent reference beam creates a complex interference pattern as a result of the difference in optical path length in reflections from the surface. An initial imaging processing step, where the interference pattern is subtracted from a known reference image, reveals the temporal progression of the 3-D particle displacement as a result of the seismic

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event. Furthermore, the signal to noise ratio may be improved by choosing multiple reference images to reduce speckle decorrelation effects. A final image processing step produces absolute intensity signal of the change in optical path as a result of said 3-D particle displacement. Finally, the intensity

5   signal is then subjected to signal processing steps which recover the seismic S-wave signals in question.

Due to the relative movement between surface and the "camera", the speckle pattern seen by the light detector may change within the seismic time. When

10   the camera is moving, the speckle pattern moves very fast and therefore the speckle monitoring must be carried out much more often than every 1ms to be able to detect/recognise and therefore monitor the same speckle group every ms.

15   Due to the seismic wavelengths, the particle velocity may be in phase within a 5m disc on the surface. Therefore groups of spatial distributed cameras can be used to increase signal to noise ratio in one seismic recording channel.

In one embodiment the monitoring apparatus comprises video recording

20   apparatus. The video recording apparatus may include one or more cameras operating on the basis of visible light. By detecting the changing positions of selected surface objects in pictures taken with several cameras, the 3D-particle velocity can be calculated using standard photogrammetry principles.

25   Due to slower variation in these full field wave field measurements than in the speckle pattern picture, the time sampling rate can be lower, more in the order of the seismic time sampling (ms).

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The invention is particularly suitable for marine seismics, in which the earth's surface is the sea bed, the seismic event is applied to the sea or directly to the sea bed and the monitoring apparatus is spaced above the sea bed. Preferably, the monitoring apparatus is located from 1 to 15 metres above the sea floor

5   during the response period. The detecting apparatus may additionally include a hydrophone to record P-waves separately.

The detecting apparatus may be towed, eg. as a streamer or series of streamers behind a surface or submarine vessel. Thus, the detecting apparatus preferably

10   comprises a plurality of monitoring devices mounted on a plurality of cables, the monitoring devices on each cable preferably being spaced from each other by a distance which is less than the wavelength of the transmitted seismic event to prevent spatial aliasing of the recorded wavefield. Alternatively, it may be located on a self-propelled submarine vessel. In such an arrangement, the

15   vessel is preferably unmanned and would preferably include an rf transmitter/receiver and aerial, an acoustic modem, an acoustic housing sensor, a bottom sensor, a depth sensor and an acoustic tracking system, in addition to the monitoring apparatus. In either case, the analysing step should include the elimination from the detected response of noise representing disturbances

20   caused by the motion of the detecting apparatus. This motion can be measured by three independent accelerometers and diameters and then subtracted from the relative motion measured by the camera.

Preferably, the particles whose movements are detected are sand particles on

25   the sea floor.

Preferably, the seismic event comprises a seismic wave having a wavelength in the range 5 to 100m and a duration from 2 ms to 1000ms. Depending upon the depth of the exploration target and the seismic P and S-velocities, preferably,

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the response period is from 5 to 20 seconds. The seismic event may be generated using apparatus on a surface vessel. It may be generated at the surface or below the surface of the ocean. The event may be generated at the sea bed by seismic sources using the land seismic source principles, in which

5   case P and S-waves can be generated.

The recording apparatus may be combined with the monitoring apparatus in a way similar to a video camera with a tape or other recording medium, but having three channels for stereo mapping and image analysis to recognize,

10   detect and position image objects. Alternatively, the monitoring apparatus, eg. a camera, may have its output transmitted to a remote recording device, which may be on a surface vessel.

The detecting device is preferably moving during the transmission period at a

15   speed in the range 1 to 5 m/s, more preferably 3 to 4 m/s. The sampling rate is preferably 1 to 2ms. Thus, in the case of a camera, a picture would have to be made more often than the seismic sampling (ms) ie. << 1 ms eg. 1 μs to 0.1ms and the effective number of pictures/second > 100.

20   From each picture from the cameras a 3D velocity is extracted.

Clearly, since such a camera or an Ocean Bottom Movie Recorder (OBM) is moving in the water while recording, an unwanted dynamic component is added to the movie (towing noise). Parts of this noise can be separated from

25   the recording by standard temporal and spatial filters. The noise which falls inside the frequency band of the particle velocity has to be calculated/predicted before it can be removed. The prediction of towing noise can be achieved using hydrophone measurements from single hydrophones attached to the

camera, since these are proportional to the vertical particle velocity of the sea bottom detected, and by three accelerometers attached to the camera.

The relative movement in the OBM vessels/cables can also be partly predicted/eliminated by processing data from several recorders which at the same time, but from different places on the vessel/cable more or less record the same part of the wavefront. This can be achieved with a camera separation less than a wavelength of the seismic wave. If the resolution in the recording is good enough, relative positioning of the recorders can be derived by image analysis and the towing noise can be predicted as a result.

The OBM's may be towed in a similar geometry as the marine multi-streamer spread used for pure P-wave seismic acquisition, but at a depth as close as possible to the sea bottom.

The invention may be carried into practice in various ways and some embodiments will now be described with reference to the accompanying drawings, in which:

Figure 1 is a schematic diagram of the overall system; and

Figures 2, 3 and 4 are schematic plan views of three different data acquisition schemes.

Referring to Figure 1, the operation is controlled by a surface vessel 11. A seismic source 12 is located on the seabed 13 and a series of mobile camera units 14 (of which two are shown) monitor the response at the seabed 13 to a seismic wave generated by the source 12. The camera units 14 are positioned about a metre above the seabed 13.

The camera units 14 each include a light transmitter, a receiver, a hydrophone, an accelerometer and a processing unit. The transmitter transmits light in the form of expanding rays, concentrated rays, modulated light and/or three

5 independent rays. The receiver may comprise a full field array, a coupled array or a single detector.

The hydrophone is present to measure seismic P-waves above the sea bottom 13. The accelerometer measures camera oscillations in the 0-200 Hz range.

10 The processing unit serves to filter noise (camera oscillations) from the measurements taken, to recognise and detect image objects, to measure image object values and convert those values to particle velocities.

In use, the source 12 generates a seismic wave with a response which lasts for a

15 period of 5 to 20 seconds which propagates through the bedrock 15 as P- and S-waves. The initial seismic wave is reflected and/or refracted at various stratum boundaries and the returning P- and S-waves cause oscillations in the up to 200 Hz range at the sea bottom 13 whose surface includes mud, sand and rocks. The camera units 14 monitor the response at the sea bottom 13 by

20 applying light to the bottom 13 and recording the reflected light (ie. the cameras 14 film the bottom 13) at a sampling rate of 0.000001 to 4 ms but generally <1ms. In effect, this constitutes a movie of the particles on the sea bottom 13 as they move in response to the returning P- and S-waves.

25 The returning P-wave also progresses from the seabed 13 up through the water 16 and is detected by the hydrophone, at a sampling rate of 1 to 4 ms and this data is conveyed to the processing unit. The accelerometer conveys noise data corresponding to camera oscillations to the processing unit.

The processing unit analyses the data collected from the receiver, the hydrophone and the accelerometer and produces a record of the response of the sea bottom particles, compensated for movement of the camera. This record can then be analysed using standard principles for seismic processing

5   interpretation and characterisation of structures, stratigrapic features and rock and fluid parameters.

Thus for each seismic shot from the source 12, all camera units 14 simultaneously record the wavefield response at the sea bottom 13 in 2 to 4 ms

10   movie samples. The camera units 14 carry out a preprocessing step which includes noise reduction, resolution enhancement, and image object identification. The camera unit dynamics are calculated and removed from the movies. Then V_x, V_y and V_z (the three velocity components of the S-wave) and P (the pressure from the P-wave) are derived and stored on four seismic

15   traces. This is repeated each 2 to 4 ms.

In an alternative embodiment, the seismic source is not at a fixed location on the seabed, but is in fact a moving P-wave source which may for example be located on the vessel 11. The P-wave generated travels through the water 16

20   and into the bedrock 15 where it propagates and is reflected/refracted as P- and S-waves as before.

Figure 2 shows an arrangement in which the seismic source 21 is moving, and which includes an array of camera units 22 which is moving and also a seismic

25   receiver 23 which is moving. Four cameras are shown in each array though there could be a greater number. An ideal arrangement would include 1 to 3 sources at a spacing of 50 to 400 m. The seismic receiver 23 is spaced from the sources also by a distance of 25 to 400 m and records for 5 to 20 seconds (depending on the transmission period) at a sampling rate of 1 to 4 ms. The

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camera units 22 and seismic receiver 23 move at a speed of 1 to 5 ms. The bottom source is fixed while the floating, towed source is moving. The seismic receiver is the centre where all measurements are stored, where the steering is controlled, where energy can be distributed from, and where the operators are

5   housed. This is similar to a seismic vessel which tows a seismic source and receivers today, and which would record/store the seismic information.

Figure 3 shows an alternative arrangement in which the sources 31, optimally 1 to 3 in number, are moveable at a speed of 1 to 5 ms, while the camera units 32

10   and seismic receivers 33 are fixed. The spacings are similar to those in the previous arrangement.

Figure 4 shows a third arrangement, corresponding to Figure 1, in which the sources 41 (again optimally 1 to 3 in number) are fixed, while the camera units

15   42 and the seismic receiver 43 are moveable. The spacings and speeds are as for the first arrangement.

The camera units would normally be mounted on or connected to cables which are towed behind a vessel or by a dedicated submarine propulsion device. The

20   position of the cameras relative to the seabed is determined by acoustic techniques and the cables are steered by "wings" on the cables. Vertical forces on the cables are balanced by weights or ballast. The cables provide mechanical connection between an array of camera units and also provide energy and communication convections. In a typical arrangement there are

25   several cables, each towing an array of camera units.

The vessel or towing device includes navigation equipment and data storage, through the camera units also have data storage.

Alternatively, the connection between the camera units may be wireless eg. a
radio connection either instead of or in addition to the cables.

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